been somewhat disappointing. Neither the 24-hour periods of highest or lowest evaporation at Grand Junction regularly precede the corresponding periods at Fremont, which lies about 170 miles due east. In the Sheridan–Black Hills–Nebraska series the sequence of events appears to be still less regular, although as a general rule the eastward movement can be traced. It appears that both local disturbances and deviations of the cyclonic centers from a regular course inject too many elements of uncertainty to make it practical to forecast the progress of evaporation at any distant point. With the information which is available to the Weather Bureau, it is probable that the rate of evaporation could be forecast, in general terms and for broad regions, as accurately as rainfall and temperatures are now forecast, but it is very doubtful whether this would serve the same purpose as an evaporation record obtained in each locality and subject to local influences.

To close what must be a merely tentative discussion of the evaporation factor as related to forest fire hazards, it may be said:

The records of evaporation obtained at six points during the season of 1923 indicate clearly the character of the variations at any single point and between stations in the same general region. They suggest that the evaporation record comprises a simple means for integrating all of the factors which accompany the periodic changes in barometric pressure, and that this record may have a quantitative value greater than that of any single factor commonly recorded at weather stations—possibly, in relation to fire hazard, greater than any combination of weather elements that might be integrated by computation. It is indicated that evaporation varies so greatly from one point to another near-by point for any single day that to be practically useful to a forest supervisor the evaporation record must be of a local character. It will, possibly, be found later that records obtained in the headquarters towns are not so valuable as those which may be obtained within the forested area.

At least for the present, the absolute evaporation rate can not be considered so important a factor in the fire hazard as the general shape of the evaporation curve. The starting point for all calculations is, apparently, the time when the evaporation rate approaches zero, indicating at least a saturated atmosphere and presumably a well-moistened condition of the forest floor. Because of the importance of this zero point, still further effort should be made to improve the evaporimeter along the line of eliminating all intake of rain water.

TRANSPIRATION BY FOREST TREES.

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[Voorheesville, N. Y., December 6, 1923.]

HÖHNEL'S EXPERIMENTS.

Aside from scattered data of transpiration from cut branches and meager potometer experiments by Risler, Vogel, Hartig, and Pfaff,[1] few data are available relative to the actual transpiration rate from trees, except the experiments of Franz von Höhnel.[2]

Although published more than 40 years ago, Höhnel's results have not been presented in English otherwise than in brief abstract form. The originals contain numerous misprints, and the results have sometimes been misinterpreted and unjustified conclusions drawn therefrom. It has appeared, therefore, worth while to give these important experiments some further critical study, and present the main results in some detail in English units. Errors and misprints in the originals have been corrected, in so far as possible.

Höhnel's experiments, carried out in connection with the Austrian Forest Service in the years 1878 to 1880, give the transpiration losses and water requirement ratios for a large number of species and varieties of trees. Seedling plants 5 to 6 years old were transplanted to potometers and allowed to stand for three or four weeks to permit the earth to settle. The potometers were 7.8 to 8.2 inches in diameter and 7.5 inches high. Each contained 7.7 to 11 pounds of soil. Conical covers were used to shut out rain, openings being left for the plant stems and for watering through a cork-inserted tube.

In 1878, 44 potometers were used, 24 being exposed in the sun and 20 in the shade. Those in the shade received sunlight from 7 to 9 a. m. and 5 to 7 p. m. For the subsequent years the total number was increased to 79, of which 39 were in the sun, 29 in half shade, and 11 in the shade. The quantity of water transpired was obtained by daily weighings. Meteorological observations were taken three times daily, including temperatures in sheltered, open, and shaded locations, and rainfall and evaporation readings. For each plant the dates of leafing and defoliation were recorded, and at the end of the season the leaf crop was air-dried and weighed and the result recorded. The mean results for 1879 for each variety of tree are given in Table 1. This shows the average transpiration loss in grams from each variety of tree, and also the water requirement ratio expressed in terms of water transpired per unit of dry leaf matter produced.

The water requirement for the year as shown in Table 1 is not always precisely equal to the sum of the water requirement for the summer and winter seasons, as given in the same table. This results from the fact that the experimental data covered the period March 1, 1879, to March 1, 1880, so that in order to obtain the transpiration loss for the period November, 1879, to April 1, 1880, inclusive, the month of March, 1879, was assumed and used to represent the month of March, 1880.

In Table 2 are given the mean water requirements for the same tree in different exposures as determined in 1879. It appears that in general the water requirement ratio for broad-leaved deciduous trees in the sun is about two-thirds that for the same variety in the shade. This result would be expected, since in general any condition unfavorable to plant development increases the water requirement ratio. Actually, the quantity of water transpired from shaded plants averaged considerably more than those in the sun, as shown in Table 3. The difference in the average is mainly due to the excessive transpiration in shade by larch and Scotch pine. Out of 15 kinds of trees for which the comparison is available, 8 transpired more and 7 less in shade than in sun, the excess either way probably depending to some extent on the tree, whether it is to be classed ecologically as sun or shade loving.

[1] Forest influences. *Bull. 7, U. S. D. A.*, 1893, pp. 78-81.

[2] Höhnel, Franz R.: Water requirements of forest trees. (Ger.) *Forsch. Beg. Agrikultur Physik*, 1879, vol. 2, pp. 397–421.

Quantity of transpiration from forest growth. (Ger.) *Mitt. Forst. Veruschwesen Oesterreichs*, 1881, vol. 2, pp. 47, 90, and 287–296.

Water requirement of forest trees with reference to meteorological factors. (Ger.) *Forsch. Beg. Agrikultur Physik*, 1881, vol. 4, pp. 435–445.

The water requirements of forests. (Ger.) *Central Blatt Gesamte Forstwesen*, 1884, vol. 10, pp. 387–409.

TABLE 1.—*Höhnel's experiments on transpiration from trees, March, 1879, to February, 1880.*

Name of tree.	Exposure.	Number of tests.	Dry leaf weight.	Date in leaf.	Date bare.	In leaf.	Total transpiration.			Water requirement ratio = $\frac{\text{Water transpired}}{\text{Dry leaf weight}}$.									
							Mar. 1 to Mar. 1.	May to October.	November to April.	Year.	April.	May.	June.	July.	August.	September.	October.	May to October.	November to April.
			Gm.			*Days.*	*Gm.*	*Gm.*	*Gm.*										
Ash (*Fraxinus excelsior*).	Sun.......	2	8.79	May 5	Oct. 9	156	7,135.5	7,097	37.9	809	1.0	28.3	219	197.0	233	115	12.2	804	4.55
	Shade.....	3	3.64	May 3	Oct. 31	181	3,833	3,789	43.4	1,043	4.5	22.4	173.9	301.4	288	196.7	50.6	1,026	16.5
	Halfshade	2	17.15	May 4	Oct. 25	173	18,102	18,047	59.6	1,092	5.9	60.7	228.9	255.5	271	218	58.6	1,083	8.5
	Mean......	......	9.86	...do.....	Oct. 22	170	9,690	9,643	46.9	981	3.8	37.1	207.3	251.3	264	179.9	40.5	971	9.8
White birch (*Betula alba*).	Sun.......	2	7.57	Apr. 8	Oct. 1	160	4,721	4,624	97.8	632	10.7	103.0	134.3	157.0	190.9	29.6	2.1	616.6	15.2
	Halfshade	2	19.10	Apr. 9	Oct. 27	201	19,670	19,316	355.0	1,066	18.7	77.9	145.6	244.3	327.9	174.8	73.5	1,044.2	21.8
	Mean......	......	13.33	Apr. 8	Oct. 14	180	12,195	11,969	226.4	849	14.7	90.4	139.9	200.6	259.4	102.2	37.8	830.4	18.5
Beech (*Fagus sylvatica*)	Sun.......	7	5.98	May 6	Oct. 31	178	4,328	4,253	74.6	816	10.8	129.5	163.6	191.7	206.5	139.2	52.3	793.9	22.3
	Shade.....	5	6.51	May 5	Nov. 1	179	5,013	4,918	94.7	968	7.7	55.4	189.6	240.0	255.4	163.7	42.5	943.4	25.6
	Halfshade	1	6.77	Apr. 30	Nov. 26	210	9,111	9,020	90.3	1,346	2.7	14.6	304.3	348.4	341.7	145.1	46.6	1,332.5	13.3
	Mean......	......	6.43	May 3	Nov. 9	189	6,151	6,064	86.5	1,043	7.1	66.5	219.2	260.0	267.9	149.3	47.1	1,023.3	20.4
Hornbeam or ironwood (*Carpinus betulus*).	Sun.......	2	6.52	Apr. 15	Oct. 14	182	5,045	4,866	178.8	794	22.4	43.7	154.2	210.6	193.5	129.9	32.7	764.8	29.5
	Shade.....	2	3.57	May 1	Oct. 22	174	2,763	2,653	109.5	776	7.8	38.1	123.1	197.5	195.2	146.6	30.5	732.2	43.6
	Halfshade	2	4.71	May 17	Oct. 25	160	4,154	4,066	87.6	792	4.9	8.7	69.0	198.9	302.9	180.2	122.6	767.1	24.5
	Mean......	......	4.93	May 1	Oct. 20	172	3,987	3,862	125.3	787	11.7	30.2	115.4	202.3	230.5	152.2	61.9	754.7	32.5
Field elm (*Ulmus campestris*).	Sun.......	2	12.88	Apr. 16	Oct. 15	182	8,029	7,844	184.8	617	11.1	43.1	128.5	140.9	173.2	102.3	14.1	601.8	15.4
	Shade.....	3	3.37	May 5	Oct. 23	200	2,663	2,545	118.1	860	30.1	68.4	181.2	194.7	205.9	139.9	29.2	819.9	40.4
	Mean......	......	8.12	May 10	Oct. 19	191	5,346	5,195	151.4	738	21.1	55.7	154.8	167.8	189.5	121.6	21.6	710.8	27.9
"Stiel" oak (*Quercus pedunculus*).	Sun.......	1	6.63	May 3	Oct. 15	165	3,012	2,913	99.0	454	4.5	60.5	103.3	112.3	92.1	60.8	1.0	439.4	14.9
"Trauben" oak (*Quercus sessilifolia*).	Sun.......	1	9.55	May 7	Oct. 23	169	4,896	4,698	197.5	513	6.3	22.4	89.0	82.6	140.5	122.9	34.6	491.9	20.7
	Shade.....	1	2.71	Apr. 28	Oct. 29	184	2,891	2,811	80.2	1,067	11.6	30.4	172.9	225.9	271.6	242.2	89.9	1,032.8	33.8
	Mean......	......	6.13	May 2	Oct. 26	176	3,893	3,754	138.8	790	8.9	26.4	130.9	154.2	206.0	182.5	62.2	762.3	27.2
"Zerr" oak (*Quercus cerris*).	Sun.......	4	11.18	May 5	Oct. 24	172	4,557	4,435	122.4	411	2.2	11.0	87.6	86.4	132.8	65.6	16.5	400.2	10.9
	Halfshade	3	17.13	May 12	Nov. 5	177	14,384	14,173	210.9	927	2.3	36.3	120.8	208.2	295.1	174.1	59.5	894.3	32.7
	Mean......	......	14.15	May 9	Oct. 30	174	9,470	9,304	166.6	669	2.25	23.6	104.2	147.3	213.9	119.8	38.0	647.2	21.8
Black alder (*Alnus glutinosa*).	Sun.......	1	11.8	Apr. 9	Oct. 23	197	4,941	4,612	329.4	419	22.1	45.6	71.7	115.0	74.2	61.1	23.3	390.8	27.9
	Shade.....	1	4.8	...do.....	Oct. 29	206	6,058	5,538	519.9	1,262	95.1	195.1	253.9	339.2	175.1	140.6	49.9	1,153.7	108.3
	Mean......	......	8.3	...do.....	Oct. 26	201	5,499	5,075	424.6	840	58.6	120.3	162.8	227.1	124.6	100.8	36.6	772.2	68.1
Gray alder (*Alnus incana*).	Sun.......	3	18.27	Apr. 10	Oct. 18	191	9,361	9,064	296.7	537	12.3	41.5	149.4	108.5	141.6	61.0	18.2	520.3	16.8
	Shade.....	3	4.64	Apr. 15	Oct. 12	169	3,850	3,672	178.4	819	28.3	40.3	150.1	218.3	187.8	137.4	44.5	781.1	37.4
	Mean......	......	11.45	Apr. 12	Oct. 15	180	6,605	6,368	237.5	678	20.3	40.9	149.7	163.4	164.7	99.2	31.3	650.7	27.1
Sycamore maple (*Acer platinoides*).	Sun.......	2	14.55	Apr. 8	Oct. 12	186	5,410	5,325	85.2	368	4.0	31.1	85.6	95.4	85.9	60.2	3.9	362.3	5.9
	Shade.....	2	4.38	Apr. 6	Oct. 29	205	2,945	2,887	58.1	672	8.6	71.7	147.0	140.8	166.3	110.4	22.1	658.4	13.2
	Mean......	......	9.46	Apr. 7	Oct. 20	195	4,178	4,106	71.6	520	6.3	51.4	116.3	118.1	126.1	85.3	13.0	510.3	9.5
Mountain maple (*Acer pseudoplat*).	Sun.......	3	9.76	Apr. 19	Oct. 1	165	5,435	5,315	119.9	549	6.9	47.3	161.1	126.9	161.9	38.2	3.9	537.0	12.6
	Shade.....	1	5.98	Apr. 10	Oct. 15	188	3,722	3,575	147.0	622	20.3	42.0	101.2	165.8	161.3	111.0	16.4	597.7	24.6
	Half shade	2	22.15	May 10	Oct. 16	159	16,214	16,111	102.7	734	0.9	55.3	130.6	162.4	239.8	115.0	25.9	729.0	4.6
	Mean......	......	12.63	Apr. 24	Oct. 11	171	8,457	8,334	123.2	635	9.4	48.2	130.9	151.7	187.6	88.1	15.4	621.2	13.9
Field maple (*Acer campestre*).	Shade.....	1	2.40	Apr. 10	Oct. 29	202	3,074	2,956	118.3	1,281	41.7	87.6	234.4	272.2	306.9	242.5	76.7	1,232.0	49.3
Linden (*Tilia grandifolia*).	Sun.......	1	7.40	Apr. 25	Sept. 29	157	7,167	7,099	66.5	968	3.6	57.5	309.9	268.8	283.1	38.6	1.4	959.3	8.9
	Shade.....	1	3.32	Apr. 9	Oct. 29	203	3,677	3,525	151.6	1,107	35.9	65.7	209.7	243.5	310.6	170.3	62.0	1,061.9	45.5
	Mean......	......	5.36	Apr. 17	Oct. 13	180	5,422	5,312	109.1	1,038	19.7	61.6	259.8	256.1	296.8	104.4	31.7	1,010.6	27.2
Aspen (*Populus tremula*).	Sun.......	1	5.52	Apr. 20	Oct. 15	178	4,820	4,679	141.3	873	21.6	84.4	165.3	185.3	246.1	142.3	24.2	847.5	25.6
Service berry or beam tree (*Sorbus tormin*).	Shade.....	1	1.56	...do.....	Oct. 29	182	2,727	2,635	91.9	1,748	31.8	90.6	251.4	357.4	555.4	345.4	88.9	1,689.1	58.9
Larch (*Larix europea*).	Sun.......	1	0.74	Apr. 15	Nov. 30	229	948	906	41.7	1,281	28.2	71.6	108.2	160.9	217.9	446.6	219.5	1,224.8	56.3
	Half shade	1	15.20	Apr. 7	...do.....	237	15,929	15,422	506.9	1,048	29.7	60.0	144.1	244.6	331.1	169.0	65.6	1,014.6	33.3
			7.97	Apr. 11	...do.....	233	8,438	8,164	274.3	1,165	28.9	65.8	126.1	202.7	274.5	307.8	142.5	1,119.7	44.8
Spruce (*Abies excelsa*).	Sun.......	3	27.0	....	....	365	6,346	5,113	1,232.2	251	14.2	21.2	60.6	52.5	43.9	29.8	15.1	203.2	47.6
	Half shade	2	38.3	May 19	....	365	10,503	9,235	1,268.6	303	7.2	27.4	46.8	63.5	84.3	39.1	11.2	267.4	35.2
	Shade.....	3	28.85	....	....	365	4,691	3,938	752.6	171	5.2	16.0	26.4	58.2	32.5	22.4	25.7	144.5	26.3
	Mean......	......	31.38	....	....	365	7,180	6,096	1,084.3	242	8.9	21.5	44.6	58.1	53.6	30.4	17.3	205.0	36.5
Fir (*Abies pectinata*).	Sun.......	3	36.55	....	....	365	....	3,044	....	....	2.7	8.1	12.3	17.2	15.4	9.4	4.3	67.8	....
	Shade.....	1	29.0	....	....	365	2,793	2,566	227.0	96	2.07	4.9	13.5	19.5	24.5	18.6	7.4	88.5	7.8
	Mean......	......	32.77	....	....	365	....	2,805	....	....	1.38	6.5	12.9	18.3	19.9	14.0	5.8	78.1	....
Scotch white pine (*Pinus silvestris*).	Sun.......	3	23.05	....	....	365	2,699	2,334	365.0	116	4.2	9.8	18.6	16.1	16.5	17.6	8.8	100.9	15.4
	Half shade	1	193.0	....	....	365	20,191	19,002	1189	105	1.1	2.07	13.2	27.7	28.6	21.0	5.9	98.5	6.2
	Mean......	......	108.02	....	....	365	11,445	10,668	777	110	2.6	5.9	15.9	21.9	22.5	19.3	7.3	99.7	10.8
Black Austrian pine (*Pinus larico*).	Sun.......	2	26.1	....	....	365	2,689	2,245	443.5	101	1.8	4.6	14.5	19.6	22.7	15.2	7.7	84.0	16.9
	Shade.....	2	15.85	....	....	365	2,144	1,819	325.4	145	5.3	15.4	28.7	25.6	28.3	18.0	7.2	123.4	21.8
	Mean......	......	20.97	....	....	365	2,416	2,032	384.5	123	3.5	10.0	21.6	22.6	25.5	16.6	7.4	103.7	19.3

TABLE 2.—*Comparative water requirement ratios (transpiration per unit dry-leaf matter) for trees grown in different exposures—Höhnel's experiments of 1879.*

Tree.	All tests.		In shade.		Half shade.		In sun.	
	Number.	R_w.	Number.	R_w.	Number.	R_w.	Number.	R_w.
Ash	7	983	3	1,031	2	1,089	2	805
Beech	16	860	5	951	4	841	7	805
Birch	4	845	......	......	2	1,062	2	627
Hornbeam	6	759	2	740	2	750	2	787
Elm	5	755	3	840	......	......	2	613
Gray alder	6	671	3	809	......	......	3	532
Oak	3	662	1	1,044	......	......	2	471
Maple	6	618	1	618	2	730	3	544
Oak	7	614	......	......	3	896	4	402
Sugar maple	4	517	2	668	......	......	2	366
"Common" oak	1	444	......	......	......	......	1	444
Oak	2	771	1	1,044	......	......	1	498
Black alder	2	831	1	1,249	......	......	1	412
Field maple	1	1,273	1	1,273	......	......	......	......
Linden	2	1,030	1	1,098	......	......	1	963
Aspen	1	869	......	......	......	......	1	869
Beam	1	1,721	1	1,721	......	......	......	......
Broad leaf woods	74	789	25	944	15	888	34	627
Spruce	8	206	3	150	2	275	3	217
Scotch pine	4	104	......	......	1	100	3	105
Austrian pine	6	100	2	129	2	85	2	86
Fir	4	76	1	90	......	......	3	70
Evergreen needle-leaved	22	135	6	133	5	164	11	123
Larch	2	1,149	......	......	1	1,044	1	1,253

TABLE 3.—*Actual transpiration losses, in grams, from seedling trees in different exposures, May–October, 1879. (Höhnel's data, 5½-year seedlings).*

	In sun.		Shade.		Half shade.		Mean.[1]	
	Number.	Grams.	Number.	Grams.	Number.	Grams.	Number.	Grams.
Ash	2	7,097	3	3,789	2	18,047	7	9,643
Birch	2	4,624	......	......	2	19,316	4	11,969
Beech	7	4,253	5	4,918	1	9,020	13	6,064
Ironwood	2	4,866	2	2,653	2	4,066	6	3,862
Elm	2	7,844	3	2,545	......	......	4	5,195
Oak[2]	1	4,698	1	2,811	......	......	2	3,754
Do[3]	4	4,435	......	......	3	14,173	7	9,304
Black alder	1	4,612	1	5,538	......	......	2	5,075
Gray alder	3	9,064	3	3,672	......	......	6	6,368
Maple[4]	2	5,325	2	2,827	......	......	4	4,106
Do[5]	3	5,315	1	3,575	2	16,111	6	8,334
Linden	1	7,099	1	3,525	......	......	2	5,312
Larch	1	906	1	15,422	......	......	2	8,164
Spruce	3	5,113	2	9,235	3	3,938	8	6,096
Fir	3	3,044	1	2,566	......	......	4	2,805
Scotch pine	3	2,334	1	19,002	......	......	4	10,666
Austrian pine	2	2,245	2	1,819	......	......	4	2,032
Means	......	4,600	......	5,590	......	......	......	......

[1] Mean of the means for sun, shade, and half shade.
[2] "Trauben."
[3] "Zerr" oak.
[4] Sycamore maple.
[5] Mountain maple.

The mean values of the water requirement ratios obtained from experiments in each of the different years are shown in Table 4. With reference to this table it should be noted that the values given are averages for all plants of a given kind, regardless of exposure. With reference to the results given in Table 4 it will be noticed that there was in general progressive increase in the water requirement ratio from year to year. The results for the years 1879 and 1880 are much more concordant with each other than either is with the results for 1878, which latter are very small. Zon[8] (p. 234) states:

The difference in the amount of transpiration in different years is explained by the fact that the years 1879 and 1880 had more rain and therefore more water penetrated the soil.

[8] Zon, Raphael: Forests and water. *National Waterways Comm. Final Report.* Washington, 1912, Appendix V, pp. 205-273.

Actually, this would more probably cause a decrease of the water requirement ratio rather than an increase such as actually occurred. The relative amounts of dry leaf production in the two years are shown in Table 5. In view of the well-known fact that the use of potometers of inadequate size increases the apparent water requirement ratio, it seems probable that the larger values of 1879 and 1880 may have been in part due to this cause. However, Fernow[1] (p. 78), discussing these experiments, suggests that the increased water requirement after 1878 was due to the later experimental seasons being more favorable to transpiration. Unfortunately, complete meteorological data accompanying the experiments are not published by Höhnel. Such data as are available are included in Table 6. It appears that the air temperatures were not materially different in 1879 from those in 1878, although in general they were slightly higher. The manner in which the evaporation was measured is uncertain. A Piche evaporometer is mentioned, but the published results (see Table 6) are very much less than would naturally be obtained from either this instrument or from an ordinary open water atmometer. From known data and the published air temperatures, the approximate evaporative capacity has been computed for the seasons 1878 and 1879, as shown in Table 7. The amounts for the growing seasons in the two years are practically identical. The number of plants was approximately doubled in 1879. All the available data indicate that larger transpiration ratios for the later years were probably caused, in part at least, by inadequate size of potometers for the larger plants.

Referring to Table 4, the lower water requirement ratio for 1878 is in part due to the fact that the experiments do not include the month of May for that year. The data for 1879 show that the total water requirement for the months of May to October, inclusive, is 10 to 15 per cent greater than that for June and November. This results from the fact that the transpiration loss drops off very rapidly after the 1st of October, and is very slight for November. The difference between the transpiration for November, which is included, and May, which is excluded in the result for 1878, amounts to 10 or 15 per cent of the total. Even with this correction, there is still a marked progressive increase in the water requirement ratios between 1878 and 1880.

TABLE 4.—*Average water requirement ratios for trees, Höhnel's experiments, growing season.*

Tree.	1878[1,2]	1879[1,3]	1880[1,3]	Mean.[1]	1879, Weighted mean.[4]
1	2	3	4	5	6
Birch	680	845	918	814	830
Ash	567	983	1,018	856	971
Hornbeam	563	759	872	731	755
Beech	472	860	914	749	1,028
Sycamore maple	463	517	612	531	510
Mountain maple	436	618	704	586	621
Elm	407	755	823	662	711
Oak "Stiel" Oak "Trauben"	283	622	692	532	600
Oak "Zerr"	253	614	492	453	647
Spruce	58.5	206	140	134.8	205
Scotch pine	58.0	104	121	94.3	99.7
Fir	44.0	72.5	94	70.2	78.1
Austrian pine	32.1	100.0	70	67.4	103.7

[1] Direct averages regardless of relative numbers of sun and shade plants.
[2] June to November, inclusive.
[3] April to October, inclusive.
[4] Sun, shade and half shade plants each given equal weight. These data are for May to October, inclusive.

TABLE 5.—*Comparison of Höhnel's transpiration data for 1878 and 1879.*

Tree.	Dry leaves.		Total transpiration.		Water requirement ratio.	
			June to November.	May to October.	June to November.	May to October.
	1878	1879	1878	1879	1878	1879
	Grams.	*Grams.*	*Grams.*	*Grams.*		
Ash	6.51	9.86	3,508	9,643	567	971
Birch	4.05	13.33	2,569	11,964	690	830
Beech	4.21	6.43	1,430	6,064	444	1,023
Ironwood	3.32	4.93	2,064	3,862	562	754
Elm	5.66	8.12	2,560	5,195	442	711
Oak	7.30	8.97	1,760	5,324	275	616
Fir	49.68	32.77	2,378	2,805	5,030	78.1
Pine	31.5	108.02	1,251	10,668	4,504	99.7
Maple	5.28	8.16	1,698	5,236	345	787
Linden	3.65	5.36	2,284	5,312	615	1,011
Aspen	4.70	7.97	3,494	8,164	743	1,120

TABLE 6.—*Meteorological data accompanying Höhnel's experiments on transpiration by trees.*

Month.	Air temperature.		Evaporation, free water surface.		Precipitation.
	Open.	Shade.	Sun.	Shade.	
1878.	*° F.*	*° F.*	*Inches.*	*Inches.*	*Inches.*
June [1]	64.9	62.8	1.44	1.07	....
July	63.3	62.4	1.45	1.38	....
August	63.7	63.5	.86	1.01	....
September	59.2	59.3	.66	.76	....
October [2]	49.1	50.9	.39	.63	....
1879.					
April	....	47.8	....	....	3.91
May	....	53.1	1.17	....	6.06
June	....	64.9	1.86	....	4.31
July	....	62.6	1.77	....	4.10
August	....	65.1	1.81	....	1.57
September	....	59.4	1.40	....	1.33
October	....	46.0	.76	....	2.09
May–October	....	....	....	....	19.46

[1] June 14–30. [2] Oct. 1–10.

TABLE 7.—*Calculated evaporation capacity for temperature of air in shade, with 70 per cent humidity, and wind 5 miles per hour.*

Month.	Θ_a.	E_c.
1878.		
June	62.8	6.30
July	62.4	6.20
August	63.5	6.50
September	59.3	5.60
October	50.9	4.10
		28.70
1879.		
April	47.8	3.60
May	53.1	4.50
June	64.9	6.80
July	62.6	6.20
August	65.1	6.80
September	59.4	5.60
October	46.0	3.40
		28.80
April–October	....	36.90
May–October	....	33.30

Referring to Table 5 it will be noted that the dry leaf production in 1879 was in general much greater than in 1878, the increase averaging 50 per cent at least. This would indicate that the seedlings suffered severely in transplanting, and did not make any material growth in the first year. The actual amounts of transpiration in 1879, allowing for differences in the months covered in the two seasons, were as a rule at least double those in 1878. This results in part from the larger extent of leaf surface and in part from the higher water requirement ratios. As already pointed out, the meteorological data while incomplete, do not, as far as they go, afford a sufficient basis for explanation of these differences. An hypothesis which is consistent with the facts is that in 1878 the trees suffered a severe set-back from transplanting but had sufficient root space in the potometers so that while the leaf production and actual transpiration are both low, the water requirement also is low. In the subsequent years, growth tended to normality, but the crowding of the root systems by the small size of the potometers produced a progressive increase in the water requirement. From these considerations the results for 1878 are of doubtful utility. Those for 1880 probably give too high water requirement ratios. Those for 1879 are the most nearly normal.

The results for 1879 do not in general differ materially from the mean of the three years; however, since the number of potometers in use in 1879 and 1880 was double that in 1878, the values for 1879 represent a better balanced average for sun, shade, and half shade conditions than those of 1878. Since it is not advisable to combine the years 1879 and 1880, on account of apparently excessive transpiration ratios for the latter year, the best available interpretation of these data for practical uses appears to be the utilization of the weighted mean results for 1879, as shown in column 6 of Table 4.

BASIS OF APPLICATION OF HÖHNEL'S RESULTS.

Höhnel's published results have been available for 40 years but have received little application owing to the lack of certain data. In conjunction with the original results, the dimensions of the experimental trees are not given, but only the age and the weight of dry leaf matter produced. The final results, being expressed in terms of water requirement ratio per unit of dry leaf matter produced, apparently require for their practical application to full-grown trees the determination, directly or indirectly, of the average annual weight of dry leaf matter. Data regarding the weight of leaves produced by different kinds of trees are very limited. Höhnel estimated a 50 to 60 year old beech to have 35,000 leaves; a full-grown birch, standing in the open, 200,000 leaves. The transpiration from beech was estimated as 22 pounds, daily, which for 500 trees per acre, would be equivalent to 7.28 inches depth on ground area per season.

Höhnel estimated that a fully stocked beech stand, 115 years old, consumed from 1,560 to 2,140 tons of water per acre, or a depth of 13.86 inches. Numerous estimates of water consumption by forests have been published purporting to be based on Höhnel's data. In general such estimates ultimately rest on measurements made from a single full-grown tree of a single variety, and represent some assumed average forest stand, and are not applicable to other conditions.

In view of the great importance of the problem of forest water consumption and of the extent and relative completeness of Höhnel's data, it has seemed desirable to find, if possible, some rational basis of application of these results. For this purpose leaf crop determinations were made by the author on well-developed trees of most of the kinds experimented on by Höhnel. If, then, it may be fairly assumed that the weight of the leaf crop for a given size of tree depends on the diameter and height of tree, it becomes possible to apply Höhnel's data to the calculation of transpiration, using data ordinarily obtainable, namely, the diameter, height, and number of trees of each species on a given area.

LEAFAGE DETERMINATIONS FOR VARIOUS TREES.

The grounds adjoining the author's laboratory includes wide variety of topographical and ecological conditions, ranging from deep ravines to steep ridges with lower river bottoms and marshy tracts. Trees of most of the species and similar varieties to those experimented on by Höhnel are indigenous to this area, and leaf crop determinations thereon were made in 1921.

The method pursued consisted in cutting down mature trees of each species or variety, with the exception of beech, for which the only specimen available was retained for ornamental purposes. In the case of trees cut down, the two butt diameters, total height of tree and height and two diameters of crown were measured, and the number of leaves determined. In the case of broad-leaved trees this was accomplished by direct counting; the branches were trimmed and cut to a convenient size for the purpose and mixed samples of typical leaves were secured in all cases. The samples were placed in trays or, in case branches were used, on wire screens, and were dried in a loft at air temperature for eight weeks. For deciduous trees two leaf samples were then selected, containing usually about 100 leaves each. These were accurately weighed on a sensitive torsion balance. In the case of hemlock the diameters of all branches were measured and recorded. Branches of several diameters were selected and preserved as samples; leaves were stripped from each branch and weighed separately. A relation curve between diameter of branch and dry leaf weight was then derived and applied to all branches, and the total leaf weight was determined indirectly. In the case of pines the number of leaf fronds on each tree was counted and samples, each containing a given number of fronds, were dried and afterwards weighed. For the beech, all branch diameters were measured, leaf counts were made from several sample branches of different diameters cut off for the purpose. A relation curve was then established between branch diameter and number of leaves, from which the total number of leaves on the tree was estimated and the total leaf weight determined by application of the results obtained from weighing dried leaf samples.

The beech tree was in a hedge bordering a pond but standing on upland 10 feet above the pond level. The elm, hornbeam, and basswood trees were from the margin of a thicket, bordering a swampy area, but the trees themselves standing on upland several feet above the swamp. The other tree samples were all from the interior of an extensive forest. Care was used to select sound trees where possible, and those which were developed normally, and which were neither overexposed to the light nor overcrowded. The samples were taken early in September, 1921, before frost and before defoliation began, but at a time when the leaf crop was mature. The ages of the trees were determined by counting the growth rings. In addition to the larger trees described, samples of thrifty young trees, sometimes two or three of each variety, were cut and measured, the leaves counted, and the leaf weight estimated from the unit weights per 100 dry leaves determined from experiments on the larger trees. The data for the two classes of trees are given in Tables 8 and 9.

The results given in Table 8 are for trees averaging about 6 inches diameter by 40 feet height and generally about 50 years of age. Table 9 contains similar results for much younger trees, 5 to 10 years of age. Column 9 of each table shows the air-dry weight of leaves per unit of diameter-height of the tree. Column 15 of each table gives the ratio of the air-dry weight of leaves to a factor determined by multiplying the circumference by the height of the tree crown. This factor is approximately proportional to the surface area of the crown. These ratios for the smaller trees are, however, uncertain, owing to the extremely irregular contours of crowns of very young trees. Comparing the ratios of leaf weight to the crown area factor, column 15, for the two tables, it appears that in general this ratio is larger for the 50-year-old than for the young trees. This would naturally be expected from the following considerations. The volume inclosed by the leaf mass of a typical tree may be looked upon as a solid of revolution, generated about the axis of the tree trunk, but with a hollow core. The whole volume inclosing the leaves is shaped something like an ordinary glass telephone insulator in the case of typical hardwoods, like the maple, but ranges in form for other trees from a hollow cone for hemlocks to a hemisphere for oaks. The leaf mass if of varying thickness in different kinds of trees but in trees of a given species the thickness of the leaf mass increases with age of the tree up to a certain limit, so that for very young trees the thickness of the leaf mass is less and the weight of leaves per unit of surface area of the crown is less than for older trees.

TABLE 8.—*Leaf production, larger trees.*

Kind of tree.	Diameter.	Age.	Height.	Diameter × height of tree 2×4.	Number of leaves, total.	Weight per 100 leaves.	Total air-dry weight of leaves.	Ratio 8/5	Height to crown.	Height of crown.	Diameter of crown.	Circumference of crown.	Circumference × height of crown 11×13.	Ratio 8/14
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Inches.	*Years.*	*Feet.*			*Ounces.*	*Ounces.*		*Feet.*	*Feet.*	*Feet.*	*Feet.*		
Hickory	8.06	54	42	338	14,220	1.165	165.66	0.490	32	10	17	53.41	534	0.310
White pine	8.06	47	42	338	[1] 5,940	4.45	264.33	.782	32	10	17	53.41	534	.495
Black ash	4.87	52	40	195	16,270	.437	71.10	.364	31	9	12	37.70	339	.210
Poplar	6.12	45	40	245	2,771	1.764	48.88	.199	30	10	12	37.70	377	.129
Soft maple	3.75	32	33	125	4,061	1.05	42.64	.341	8	25	13	40.84	1,020	.0418
Black oak	6.25	48	41	256	8,482	2.302	195.25	.762	24	17	14.5	45.60	775	.252
White oak	6.06	48	41	248	9,663	1.358	131.22	.530	13	27	11.5	36.13	975	.135
Chestnut	6.87	55	49.6	341	2,687	1.766	47.45	.139	36	13.6	9.5	29.84	541	.088
Ironwood	3.12	42	31.5	97	9,476	.40	37.90	.391	11.5	20	12	37.70	754	.050
Hemlock	8.12	95	35.1	285	....	....	342.0	1.200	8	27.1	13.5	42.41	1,149	.298
Yellow pine	5.87	45	43.6	256	....	....	189.5	.740	29.3	14.3	7	21.99	314	.603
Water beech	2.25	18	18	40.5	2,369	.470	11.3	.275	3	15	12.5	39.27	590	.0189
Basswood	8.25	50	45.2	373	16,128	1.195	192.73	.516	18	27.2	28	87.96	2,394	.0806
White birch	3.50	22	26.5	89	2,611	1.006	26.27	.295	7	19.5	10.5	32.99	650	.0404
Black alder	3.94	19	21.7	85.5	2,688	.965	25.94	.303	1	20.7	18	56.55	1,172	.0222
Elm	4.37	15	25	109	14,366	.750	107.75	.990	6	19	10	31.42	597	.180
Beech	9.75	....	38	370	29,100	.510	148.41	.401	6	32	30	94.25	3,014	.0493

[1] Fronds.

TABLE 9.—*Leaf production, young trees.*

Kind of tree.	Diameter.	Age.	Height.	Diameter × height of tree, 2×4.	Number of leaves, total.	Weight per 100 leaves.[1]	Total air-dry weight of leaves.	Ratio[2] 8/5	Height to crown.	Height of crown.	Diameter of crown.	Circumference of crown.	Circumference × height of crown, 11×13.	Ratio 8/14.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Inches.	*Years.*	*Feet.*			*Ounces.*	*Ounces.*		*Feet.*	*Feet.*	*Feet.*	*Feet.*		
White oak	0.48	8	5.0	2.4	194	1.358	2.63	1.096	1.83	3.17	1.67	5.24	16.61	0.159
Soft maple	.47	7	6.75	3.17	240	1.05	2.52	.795	2.00	4.75	2.42	7.60	36.10	.070
Do	.21	....	2.60	.55	25	1.05	.26	.473	.60	2.00	1.25	3.93	7.86	.033
Do	.18	....	2.50	.45	27	1.05	.28	.622	.80	1.7	.75	2.36	4.01	.069
Black oak	.59	8	5.5	3.24	203	2.302	4.67	1.441	2.00	3.5	4.33	13.6	47.60	.098
Ironwood	.63	11	6.0	3.78	430	.40	1.72	.456	1.50	4.5	3.38	10.6	47.7	.036
Basswood	.53	9	5.67	3.01	282	1.195	3.37	1.120	1.5	4.17	2.25	7.06	29.4	.115
Do	.22	5	2.33	.51	38	1.195	.45	.882	.25	2.08	.58	1.83	3.81	.119
Hickory	.51	9	5.0	2.55	323	1.165	3.77	1.480	.67	4.33	1.42	4.46	19.31	.175
Chestnut	.48	10	6.16	2.96	140	1.766	2.47	.835	1.08	5.08	2.50	7.85	39.87	.0619
Black ash	.48	8	6.33	3.04	157	.437	.69	.227	2.75	3.58	2.17	6.82	24.41	.0283
Black alder	.71	11	8.42	5.97	881	.965	8.50	1.425	1.84	6.58	4.08	12.8	84.22	.101
Elm	.52	5	3.5	1.82	209	.75	1.53	.840	1.58	1.92	3.38	10.6	20.35	.075
Beech	.64	11	5.25	3.36	302	.51	1.54	.458	1.33	3.92	1.92	6.03	23.63	.0653
Hemlock	1.05	13	5.0	5.25	....	....	[3] 10.97	2.09	.25	....	4.33	13.6	....	....
White pine	2.13	18	13.75	20.3	[4] 490	1.85	9.07	.312	8.5	5.25	3.50	11.0	57.75	.157
Do	.55	8	2.67	1.47	[4] 97	....	[3] 1.02	.694	.17	2.50	1.75	5.5	13.75	.0739
Do	.36	3 (?)	1.92	.69	[4] 41	....	[3] .29	.409	.17	1.75	1.08	3.39	5.36	.0541

[1] From determinations on samples from full-grown trees, air dry.
[2] Diameter in inches×height in feet divided by leaf weight per 100 in ounces avoirdupois.
[3] Actual weight.
[4] Fronds.

DIAMETER-HEIGHT RELATIONS OF TREES.

The usual data available as a basis for determining the transpiration loss from a forest are the numbers of trees of different species and diameters. In what follows it is assumed that these data are available. If, as is sometimes the case, only the age of the forest is known, then it is assumed that the diameters are taken as the normal diameters for trees of a given age. Of course, the heights of the trees are also sometimes given in forest cruisers' tables, but in rapid forest inspection for hydrological work the diameters are more readily estimated or measured than the heights.

For the same species of trees grown in different localities the normal heights and diameters at a given age vary considerably. This is illustrated for hemlock by Table 10. It will be noted, however, that for tress of the same diameter the heights are approximately the same, although the ages at which trees reach a given diameter in different localities are often quite different. Similar data for lodgepole and western yellow pine are given in Table 11. Even for trees of the same species but different varieties the relation between diameter and height at a given age is fairly uniform, as illustrated for hickories by Table 12.

All that has been given with reference to age, diameter, and height relations for trees refers exclusively to forest-grown trees. Isolated trees in the open as a rule have less height, greater crown width, and a smaller ratio of height to diameter. It is not to be expected that the diameter-height relations will apply with accuracy to individual trees; however, in estimating the transpiration from any considerable area of forest, all that is required is the average or statistical relation. With reference to individual trees, the variations in height for a given diameter are usually maintained within well-defined limits, more nearly constant as the trees grow older, but the maximum and minimum heights for a given diameter are usually within 25 per cent of the average for the same diameters, as shown in Table 13.

TABLE 10.—*Age, height, and diameter relations for hemlock.*[1]

Age, years.	Leelanau County, Mich.		West Virginia slope type.		Tennessee slope type.		North Carolina cone type.		Otsego County, N. Y.	
	Diameter.	Height.	Diameter.	Height.	Diameter.	Height.	Diameter.	Height.	Diameter.	Height.
	Ins.	*Feet.*	*Ins.*	*Feet.*	*Ins.*	*Feet.*	*Ins.*	*Feet.*	*Ins.*	*Feet.*
20	0.7	8	0.4	......	0.2	......	......	......	0.4	7
30	1.3	12	.9	......	.9	9	1.1	15	.9	10
40	2.1	16	1.3	11	1.9	16	2.2	23	1.4	13
50	2.9	20	1.9	14	3.0	23	3.4	30	1.9	16
60	3.8	25	2.4	17	4.1	30	4.7	36	2.5	20
70	4.7	30	2.9	20	5.3	37	6.2	42	3.3	24
80	5.7	35	3.6	24	6.7	44	7.6	47	4.0	28
90	6.7	40	4.2	27	8.0	51	9.1	53	4.7	32
100	7.8	44	4.9	31	9.4	58	10.5	58	5.5	36
110	9.0	49	5.6	34	10.7	64	11.9	62	6.4	40
120	10.0	53	6.4	39	11.8	69	13.2	66	7.3	45
130	11.2	57	7.3	43	12.9	73	14.5	70	8.3	50
140	12.3	60	8.1	47	14.0	77	15.5	73	9.4	54
150	13.4	63	8.9	51	15.1	81	16.5	76	10.5	59
160	14.5	66	9.9	56	16.1	84	17.4	78	11.6	63
170	15.5	68	10.9	60	17.1	87	18.3	81	12.7	66
180	16.5	70	11.9	64	18.1	90	19.2	83	13.5	69
190	17.5	72	12.7	67	19.1	93	20.0	85	14.3	71
200	18.4	74	13.5	70	20.0	95	20.7	87	15.1	72

[1] Frothingham, E. H.: The eastern hemlock, Bull. 152, F. S., U. S. D. A. pp. 25–27.

TABLE 11.—*Variation in diameter-height relation with habitat.*

LODGEPOLE PINE.[1]

	Diameter in inches.								
	4	6	8	10	12	14	16	18	20
	Heights, in feet.								
Medicine Bow, National Forest, Wyo.	....	....	59	64	69	73	76	....	....
Slope type, Gallatin County, Mont.	41	57	66	71	74	76	78	79	81
Flat or creek type, Gallatin County, Mont.	40	50	57	63	68	73	77	80	82

[1] Ziegler: Forest tables, Lodgepole pine, *Cir. 126*, *F. S.*, U. S. D. A. p. 15.

TABLE 11.—*Variation in diameter-height relation with habitat*—Continued.

WESTERN YELLOW PINE.[3]

	Diameter in inches.								
	6	8	12	16	20	24	28	32	36
	Heights, in feet.								
Prescott National Forest, Ariz.	24	30	43	54	65	74	82	87	91
Archuleta County, Colo.	22	31	53	68	79	88	96	102	.....
Black Hills National Forest, S. D.	34	45	62	73	80	86	90	.....	.....
Flathead and Missoula Counties, Mont.	44	54	70	81	91	100	107	114	121
Butte and Madero Counties, Calif.	30	40	60	79	97	112	125	136	144
Stevens County Wash	.....	.....	.....	.....	110	115	130	142	146

[3] Idem: Forest tables. Western yellow pine, *Cir. 127, F. S.*, U. S. D. A. p. 11.

TABLE 12.—*Variation in height of young seedling hickories of different varieties.*[1]

	Age, years.					
	1	2	3	4	5	6
Shagbark	2.8	4.2	7.8	12.0	17.0	....
Pignut	3.0	5.8	8.0	12.0	17.0	....
Mockernut	3.0	4.7	8.0	12.5	20.0	28.7
Bitternut	3.5	6.3	9.5	13.3	19.5	27.0
Big shellbark	4.3	6.0	11.0	16.0	22.0	....

[1] Bolsen and Newlin: The commercial hickories, Bull. 80, F. S., U. S. D. A. p. 27.

TABLE 13.—*Variation in individual trees of Norway pine, in Bayfield County, Wis.*[1]

	Diameter in inches.													
	1	2	4	6	8	10	12	14	16	18	20	24	30	34
	Height in feet.													
Minimum	11	16	21	26	32	38	44	50	55	61	66	76	89	98
Maximum	16	28	52	72	87	97	103	107	109	112	114	117	123	127
Average	12	20	34	47	58	67	74	80	85	88	91	96	104	109

[1] Woolsey and Chapman: Norway pine in the Lake States, Prof. Paper 39, F. S., U. S. D. A., pp. 7–18.

Taking the case of a second-growth white pine in New Hampshire,[4] the constancy of the height-diameter relation and normal density of stand or stock in different habitats is illustrated by the following figures:

Quality 1: Age, 55 years; diameter, 11.8 inches; height, 80.5 feet; 354 trees per acre.

Quality 2: Age, 65 years; diameter, 11.6 inches; height, 79 feet; 348 trees per acre.

Quality 3: Age, 80 years; diameter, 11.7 inches; height, 78 feet; 318 trees per acre.

TREE GROWTH RELATIONS.

Before attempting to apply the water requirement ratio as determined by Höhnel and the author's leaf-weight determinations to practical calculation of transpiration losses, attention will be called to some facts regarding the laws of growth of trees which may throw light on the question of the validity of the assumption that the leaf crop for a given species of tree varies in proportion to the product of trunk diameter and height. The rate of growth of a tree is not in general proportional to its age.

[4] Frothingham, E. H.: White pine, *Bull. 13, F. S., U. S. D. A.*, pp. 21–22.

In nearly all cases the growth graphs are curved and there seems to be no general form of growth curve applicable to all trees. The rate of growth is a function of the habitat—trees of the same age growing in different locations have widely different diameters and heights. This is well illustrated by the data for hemlock shown in Table 10.

Transpiration loss is proportional to leaf mass of the tree crown. It is therefore desirable to find what evidence there is available in support of the assumption made that the leaf mass is proportional to the product—diameter in inches × height in feet.

TABLE 14.—*Tree crown area and volume relations.*

Species.	Diameter breast high = d.	Crown diameter.	Normal height = h.	Crown height = h_c.	Crown circumference = C_c.	Crown circumference × height.	dh.
	Inches.	*Feet.*	*Feet.*	*Feet.*	*Feet.*	*Square feet.*	
Beech	1	3	12	7	9.45	66.5	12
	5	13	44	25	40.8	1,020	220
	10	24	72	43	75.4	3,242	720
	15	31	75	45	97.4	4,383	1,125
	20	35	76	45	110.0	4,950	1,520
	25	38	77	46	119.0	5,474	1,925
Sugar maple	1	3	13	6	9.45	56.7	13
	5	13	43	20	40.8	816	215
	10	21	65	31	66.0	2,046	650
	15	27	73	35	84.8	2,968	1,095
	20	32	75	36	100.5	3,618	1,500
	25	38	77	37	119	4,403	1,925
Yellow birch	1	3	15	6	9.45	56.7	15
	5	11	37	15	34.6	519	185
	10	18	61	27	56.5	1,525	610
	15	23	70	31	72.2	2,238	1,050
	20	29	76	35	91.1	3,185	1,520
	25	35	82	38	110.0	4,180	2,100
Basswood[1]	1	3	7.8	4	9.4	37.6	7.8
	5	12	37	17	37.7	641	185
	10	18	65	25	56.5	1,412	650
	15	20	83	30	62.8	1,884	1,245
	20	22	93	32	69.1	2,211	1,860
	25	25	102	34.5	78.5	2,708	2,550

[1] Volume table not available. Normal height given is for yellow poplar.

As already noted, the thickness of the leaf mass increases with age or with diameter and height up to a certain limit at least. In order, then, that the leaf mass should be proportional to the product of diameter times height it is necessary that increase in diameter and height of crown should be somewhat less rapid than increase in diameter and height of tree trunk. The relation of breast-height diameter to crown diameter for Norway pine is illustrated by the following data:

Relation of breast-height diameter to crown diameter, Norway pine in Lake States.[5]

Trunk diameter, inches.	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Crown diameter, feet.	4	5	7	8	9	11	12	13	13	14	15	15	16	16	16	16	16	17	17

It will be noted that for trees up to 13 inches in diameter the crown diameter in feet is approximately 1.2 times the trunk diameter in inches. For further increase in trunk diameter there is, however, not a proportional increase in crown diameter.

In Table 14 data are given relative to the crown diameters and crown heights of four varieties of trees in terms of trunk diameter and trunk height. The normal age of trees of different diameters and heights have been taken

[5] Cf. footnote to Table 13.

from the Woodsman's Handbook. The trunk and crown diameters and trunk and crown heights for beech trees have been plotted in terms of age as shown on figure 1. The rate of growth in the case of beech increases with age until the tree reaches very nearly its mature height. Growth in trunk diameter continues, though at a slightly diminished rate, long after the tree has reached its full stature. Crown height is nearly a constant percentage of the height of the trunk at all ages. The crown reaches its mature height at about the same age as the trunk.

Then,

$$T_c = \frac{W_r L_r dh}{16 \times 62.4} = 0.001\, W_r L_r dh \qquad (1)$$

$$T_d = \frac{12\, T_c N}{43{,}560} = \frac{T_c N}{3{,}630} \qquad (2)$$

or

$$T_d = \frac{0.2755\, W_r L_r dhN}{1{,}000{,}000} \qquad (3)$$

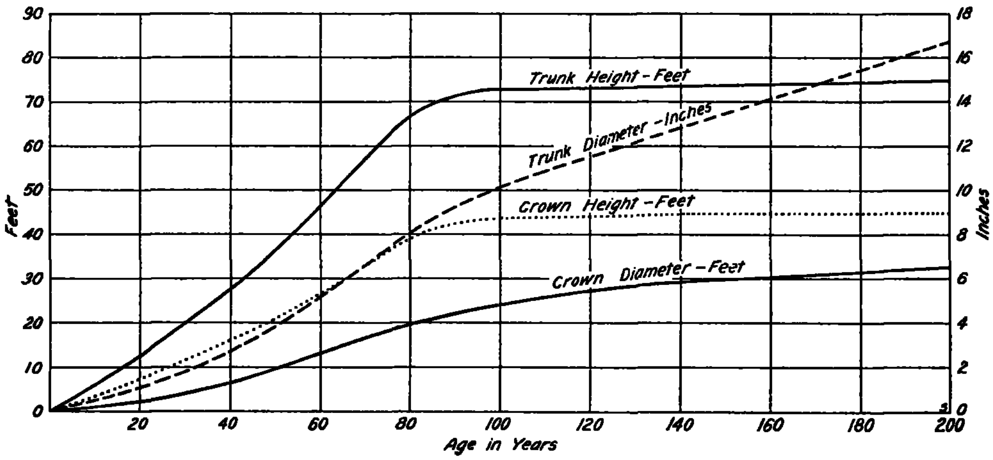

FIG. 1.—Relations between trunk and crown height and diameter and age.

Growth in crown diameter, like growth in diameter of trunk, continues after the tree and crown have reached full height, but growth in crown diameter is relatively slower than growth in trunk diameter after the full height of the tree is attained. In so far as it is possible to generalize from the limited data at present available, it appears that the crown surface is very nearly proportional to the product of trunk diameter times height until the tree reaches its mature height, after which the crown surface increases more slowly than that product; but, as already noted, this is undoubtedly compensated for in part by increase in thickness of the leaf layer. Apparently nothing better can be done at present than to assume the annual weight of leaf crop to be proportional to the product—diameter times height. It is necessary to leave the matter of finding a more precise basis of calculation of transpiration for future determination.

Calculating Forest Transpiration.

Table 15 contains the water requirement ratios for various species of trees as determined by Höhnel, together with the leaf-weight ratio or dry-leaf weight in ounces per inch-foot of the diameter-height product for these trees as determined by the author.

Let L_r = dry-leaf weight, ounces per inch-foot.

d = breast-height diameter of tree in inches.

h = height of tree in feet.

W_r = Höhnel's water-requirement ratio.

T_c = transpiration loss, cubic feet per tree.

T_d = transpiration loss expressed as a depth in inches per acre.

N = number of trees per acre.

Columns 6, 7, and 8 of Table 15 give values of T_d in inches depth on forest area for summer, winter, and the year, respectively, for a value of $dhN = 10{,}000$. Calling these values T_1, then

$$T_d = \frac{dhN}{10{,}000}\, T_1 \qquad (4)$$

TABLE 15.—*Factors for calculating transpiration from trees*[1] *(leaf-crop basis).*

Tree.	Leaf ratio L_r.	Water-requirement ratio = W_r. Höhnel, 1879.			Transpiration, T_1 inches per acre, $dhN = 10{,}000$.			Average.
		May-October.	November-April.	Year.	May-October.	November-April.	Year.	
1	2	3	4	5	6	7	8	9
Ash	0.364	971	9.8	981	0.974	0.00982	0.984	
Birch	.295	830	18.5	849	.676	.0151	.690	
Beech	.401	1,023	20.4	1,043	1.131	.0226	1.15	
Hornbeam (ironwood)	.391	755	32.5	787	.814	.0350	.850	1.05
Elm	.990	711	27.9	738	1.943	.0762	2.02	
Oak (average)	.646	616	21.3	638	1.098	.0381	1.14	
Maple (average)	.341	565	11.7	578	.533	.0110	.544	
Gray alder	[2] 303	651	27.1	678	.544	.0226	.566	......
Black alder	.303	772	68.1	840	.646	.0568	.703	......
Basswood (linden)	.516	1,011	27.2	1,038	1.44	.0386	1.48	......
Aspen	.199	848	25.6	873	.466	.0141	.480	......
Larch (tamarack)	[3] 1.20	1,120	44.8	1,165	3.698	.1482	3.864	......
Spruce	[3] 1.20	205	36.5	242	.679	.1208	.800	
Fir	[3] 1.20	78	7.8	86	.258	.0259	.284	.393
White pine [4]	.782	100	10.0	110	.216	.0215	.237	
Yellow pine [5]	.740	104	19.0	123	.213	.0389	.251	

[1] From the author's measurements for mature trees. Ounces dry leaves per inch-foot. Trunk diameter × height.
[2] Assumed same as black alder.
[3] Assumed same as for hemlock.
[4] Höhnel's Scotch pine.
[5] Höhnel's Austrian pine.

TABLE 16.—*Comparative yearly transpiration losses from even-aged full-stocked stands of different ages representing approximate maximum transpiration losses for a given age and species.*

[Numbers, diameters, and heights of trees from U. S. Forest Bureau yield tables. (For evaporative capacity=45 ins.).]

	Age, years.									
	20	30	40	50	60	80	100	120	140	160
Douglas fir, western Cascade foothills on first quality soils. $T_1=0.284$:										
Trees per acre	990	580	410	340	265	167	115	92	88	....
Diameter, average tree	4.6	6.9	8.9	10.4	12.3	16.5	20.9	24.5	25.9	....
Height, average tree	32	46	59	69.5	82	107.5	134.5	156.5	166	....
dh	147	317	525	723	1,009	1,782	2,800	3,834	4,300	....
Ndh/100	1,455	1,839	2,152	2,458	2,700	2,976	3 220	3,527	3,784	....
T	4.12	5.22	6.11	6.98	7.67	8.45	9.14	10.02	10.75	....
White pine, quality first, second growth. $T_1=0.237$:										
Trees per acre	1,322	879	583	408	311	207	154	....	....	....
Diameter, average tree	4.0	6.4	8.6	10.8	12.8	16.5	19.8	....	....	....
Height, average tree	24.5	44	61	74.5	85.5	101.5	113	....	....	....
dh	98	282	525	804	1,094	1,675	2,237	....	....	....
Ndh/100	1,196	2,479	3,061	3,280	3,402	3,467	3,445	....	....	....
T	2.83	5.86	7.25	7.77	8.06	8.22	8.16	....	....	....
Red spruce, quality first, normal full-stocked second-growth stands in New Hampshire and Vermont. $T_1=0.800$:										
Trees per acre	1,294	887	668	558	506	457	417	....	....	....
Diameter, average tree	3.8	5.9	7.5	8.6	9.3	10.1	10.8	....	....	....
Height, average tree	24	36	46	55	61	70	76	....	....	....
dh	91	212	345	473	567	707	821	....	....	....
Ndh/100	1,177	1,880	2,305	2,639	2,869	3,231	3,423	....	....	....
T	9.42	15.04	18.40	21.11	22.95	25.85	27.38	....	....	....
Hickory. T_1 (average hardwood)$=1.05$:										
Trees per acre	....	700	480	320	230	155	120	100	84	73
Diameter, average tree	....	4.0	5.0	6.2	7.2	9.0	10.5	11.8	12.6	14.4
Height, average tree	....	33	41	49	57	69	78	85	90	94
dh	....	132	205	304	410	621	835	1,003	1,134	1,354
Ndh/100	....	924	984	1,063	943	963	1,002	1,003	925	989
T	....	9.70	10.33	11.16	9.90	10.11	10.52	10.53	9.71	10.38
Beech. $T_1=1.15$:										
Trees per acre	2,524	1,526	934	598	423	269	196	157	....	....
Diameter, average tree	1.7	3.0	4.5	6.3	7.9	10.7	13.0	15.0	....	....
Height, average tree	18	31.5	44.6	56.1	66.9	84.6	97.1	106	....	....
dh	31	95	201	353	528	905	1,261	1,590	....	....
Ndh/100	782	1,450	1,877	2,111	2,233	2,434	2,472	2,496	....	....
T	8.99	16.6	21.59	24.27	25.68	28.00	28.43	28.64	....	....

Transpiration rate for various kinds of vegetation has been found to bear very nearly a relation of direct proportionality to evaporative capacity. Inasmuch as the annual evaporative capacity, E_c, for the region and conditions where Höhnel's experiments were performed was about 45 inches, it is evident that to obtain the transpiration loss in any region where the evaporative capacity E_c is different the transpiration as calculated by the formulae above given should be multiplied by a factor $\frac{E_c}{45}$.

Finally, the working formula for calculating transpiration depth from forest areas is

$$T_d=\frac{dhN}{10.000}\times\frac{E_c}{45} \qquad (5)$$

The data required are those given in conjunction with ordinary forest cruisers' reports, i. e.. *d*, *h*, and *N*, or *d* and *N*. *N* and the age of the forest alone may be used in conjunction with the age-diameter-height relations given in the Woodsman's Handbook.

In Table 16 there are given for various kinds of trees the number and sizes of trees per acre for fully stocked even forest stands. In each case the corresponding transpiration loss for a region where the evaporative capacity is 45 inches has been calculated by means of formula (5). The results are expressed opposite *T* for each age. In the case of some species of trees on which there were no experiments by Höhnel, the water requirement ratio has been assumed as equal to that for some closely related species, as indicated in the table. Comparison of the values of *T* for different species and ages of trees shows at once the wide rage of transpiration loss which may take place from different forest areas, dependent upon the composition, density, and age, or development of the forest growth. For spruce and fir, leaf weight determinations for mature trees are wanting and the transpiration values are still somewhat conjectural. As further illustrating the application of the data, calculations of the annual transpiration loss from mixed woodlands where the composition and stand are known are given on Table 17. Here again there are wide variations in the amount of annual transpiration loss, dependent upon the density, character, and stand of the different species of trees. In this calculation it has been necessary to adopt unit values of transpiration loss for a closely related variety or species in many instances. The values adopted are given in column 13 of the table.

Relative to the accuracy of the results obtained by this method of calculating forest transpiration, it may be said that they are at least consistent with what is known of this matter from other sources. In this connection it is to be borne in mind that there are three sources of water losses from a forest area: interception, transpiration, and evaporation from the soil. The interception loss can be determined with considerable accuracy from existing data. Roughly it amounts to about 15 per cent of the rainfall.

TABLE 17.—*Estimated annual transpiration by actual forest stands.*

Locality.	Tree.	Number per acre N.	Diameters.[1] From—	Diameters.[1] To—	Diameters.[1] Weighted average.	Average height.[2]	*dh.*	*Ndh.*	T_1.	*T.*	
1	2	3	4	5	6	7	8	9	10	11	12
Spruce, flat, Pittsburgh Township, N. H., virgin forest. E_e=approximately 42 inches.	Spruce	200	2	25	9.26	50	463	92,600	0.800	7.48	
	Balsam fir	275	2	17	4.78	40	191	52,525	.284	1.49	
	Yellow birch	6.2	2	35	10.10	60	606	3,757	.690	.26	
	Paper birch	22.9	2	16	6.99	54	377	7,717	.690	.52	
	Miscellaneous	3.4	2	13	3.06	30	92	313	1.05	.03	T_1 for average hardwood.
	Total									9.78	$9.78\times\frac{42}{45}$=9.13 inches annual transpiration.
Hardwood forest, Waterville Township, N. H. Average hardwood E_e=approximately 42 inches.	Spruce	88.12	2	20	6.95	42	292	25,731	.800	2.06	
	Balsam	10.68	2	15	3.40	28	95	1,015	.281	.03	
	Hemlock	3.78	2	37	16.17	69	1,118	4,226	.512	.23	T_1 for mean of spruce and balsam.
	Yellow birch	40.81	2	42	20.63	76	1,566	63,955	.690	4.41	
	Sugar maple	15.94	2	32	10.04	65	652	10,393	.544	.56	
	Beech	70.62	2	26	8.74	69	603	42,584	1.15	4.90	
	Miscellaneous	20.54	2	20	2.95	30	88	1,808	1.05	.19	T_1 for average hardwood.
	Total									12.38	$12.38\times\frac{42}{45}$=11.55 inches annual transpiration.
Flat, burned over 30 years preceeding, New Hampshire. E_e=approximately 42 inches.	Yellow birch	2			1.0	15	15	30	.690	.002	
	Spruce	22			2.5	20	50	1,100	.800	.088	
	Paper birch	20			3.1	32	99	1,980	.690	.137	
	Aspen	3			3.9	34	133	399	.480	.019	
	Balsam fir	18			4.2	33	139	2,502	.284	.071	
	Red maple	14			3.8	34	129	1,806	.544	.098	
	Striped maple	3			1.0	12	12	36	.544	.002	T_1 for black alder.
	Shadbush	5			1.0	8	8	40	.703	.003	
	Total									.42	$0.42\times\frac{42}{45}$=0.39 inches annual transpiration.
Lodgepole pine, Medicine Bow, Wyo. (Only trees over 4 inches in diameter are included.) E_e=approximately 46 inches.	Lodgepole pine	251.60	4	28	8.98	66	593	149,198	.251	.374	T_1 for yellow pine.
	Engleman spruce	9.00	4	29	9.04	49	443	4,014	.800	.32	
	Alpine fir	7.46	4	20	6.92	40	277	2,065	.284	.059	
	Aspen	.05	4	8	6.00	48	288	144	.480	.007	
	Cottonwood	.01	5	5	5.00	58	290	3	1.48	.0004	T_1 for linden.
	Total									4.126	$4.126\times\frac{46}{45}$=4.22 inches annual transpiration.
Western yellow pine, Madero County, Calif. 5,000 feet elevation. E_e=approximately 60 inches.	Incense cedar	38.45	1	59	17.18	79	1,359	52,253	.284	1.48	T_1 for fir.
	White fir	24.60	1	54	18.00	79	1,422	34,981	.284	.99	Do.
	Western yellow pine	20.65	1	84	21.71	142	3,081	63,622	.251	1.60	
	Sugar pine	19.25	1	84	22.00	108	2,376	45,738	.251	1.15	
	California black oak	2.30	1	39	16.21	72	1,167	2,684	1.14	.30	
	Total									5.52	$5.52\times\frac{60}{45}$=7.36 inches annual transpiration.
Chestnut slope, southern Maryland. E_e=approximately 52 inches	Chestnut	101.57	2	44	10.80	60	648	65,817	1.14	7.51	T_1 for oak.
	Oak	31.57	2	26	8.07	55	444	14,030	1.14	1.60	
	Beech	13.56	2	23	6.12	50	306	4,149	1.15	.48	
	Red maple	9.70	2	13	4.65	42	195	1,891	.544	.10	
	Hickory	9.14	2	10	3.70	28	104	950	1.05	.10	T_1 for average hardwood.
	Sweet gum	6.00	3	18	7.25	68	493	2,958	1.05	.31	Do.
	Yellow poplar	2.57	2	14	4.36	38	166	426	.480	.02	
	Black gum	2.43	2	12	3.63	40	145	352	1.05	.04	Do.
	Scrub pine	2.13	4	12	7.87	56	441	939	.237	.02	
	Miscellaneous	3.12	2	16	5.68	40	227	708	1.05	.07	Do.
	Total									10.25	$10.25\times\frac{52}{45}$=11.84 inches annual transpiration.
Western yellow pine, E_e=approximately 65 inches.	Black jack	13.64	4	36	13.69	65	990	13,503	.251	.34	
	Yellow pine	22.26	7	48	22.39	68	1,502	34,770	.251	.87	
	Total									1.21	$1.21\times\frac{65}{45}$=1.75 inches annual transpiration.
Virgin spruce and fir forest, Maine. E_e=approximately 36 inches.	Spruce	276.4	2	12	5.49	38	209	57,767	.800	4.62	
	Balsam fir	72.0	2	12	5.02	42	211	15,192	.284	.43	
	Total									5.05	$5.05\times\frac{36}{45}$=4.04 inches annual transpiration.
Typical Adirondack forest (Pinchot). E_e=approximately 40 inches.	Spruce	31.40			13.0	65	845	26,533	.800	2.12	
	Birch	14.00			17.1	71	1,214	16,996	.690	1.17	
	Beech	10.00			13.2	72	950	9,500	1.15	1.09	
	Hard maple	6.10			13.9	71	987	6,021	.544	.33	
	Hemlock	4.60			16.7	70	1,169	5,377	.542	.29	T_1 for average spruce and fir.
	Balsam	4.20			11.4	61	695	2,919	.284	.083	
	Soft maple	2.60			13.6	72	979	2,545	.544	.138	
	White pine, Ash, Cedar, Cherry	.54	Av.	15.3	18.4, 12.9, 14.5, 15.3	72	1,101	594	.393	.022	T_1 for average spruce, fir, and pine.
	Total									5.24	$5.24\times\frac{40}{45}$=4.66 inches annual transpiration.

[1] Diameter in inches.

[2] Height in feet.

TABLE 18.—*Seasonal distribution of transpiration. Höhnel's 1879 experiments.*

Tree.	Per cent of seasonal total, June-September.			
	June.	July.	August.	September.
Ash	23.0	28.0	29.4	18.9
Birch	19.9	28.6	36.8	14.5
Beech	24.5	29.0	30.0	16.6
Hornbeam or ironwood	16.4	28.8	32.9	21.7
Elm (field)	24.4	28.4	29.9	19.0
Oak ("Stiel" and "Trauben")	19.4	22.8	30.5	27.0
Oak ("Zerr")	17.9	25.2	36.7	20.5
Spruce	24.1	31.1	29.0	16.0
Fir	20.0	27.5	30.8	21.5
Pine (Scotch white)	20.0	27.5	28.1	23.8
Pine (black Austrian)	23.5	24.8	26.9	18.3
Average	21.2	27.2	31.0	19.8
Höhnel's measured evaporation, 1879, per cent	27.2	25.9	26.5	20.5

Evaporation from the soil surface can also be approximately determined. The total water losses are known for many areas from a comparison of the measured run-off and precipitation.

The leaf-weight ratios used in Table 15 are those for the larger trees where available. Values for larger trees were used instead of an average of those for large and small trees, because determinations of transpiration losses from larger trees are those most generally described. Comparing the leaf-weight ratios, column 9 of Tables 8 and 9, for large and small trees, it will be found that the ratios for young trees are generally, though not always, considerably the larger. In other words, trees of less than 10 years of age have more leaf weight per unit of diameter times height than mature trees. The method of calculation here used, based on leaf-weight data for mature trees, apparently leads to too small values of estimated transpiration when applied to very young trees. No certain method of correcting for this factor is at present available. In view of the fact that the thickness of the leaf layer in the tree crown becomes more nearly constant after the tree has reached a moderate size and the crown begins to have a core or hollow center, it may be fairly presumed that this error is not involved except in comparatively young trees.

A determination of the ratio $\frac{\text{dry leaf weight}}{\text{diameter} \times \text{height}}$ was made in general for only one large tree of each kind. Better results would no doubt be obtained by averaging a large number of trees of the same size and species. Furthermore, it is desirable that such investigations should be carried out for various sizes or ages of trees of the same species. In spite of the necessity of cutting down many trees and the great amount of labor involved in a leafage determination, even for a single tree, it is to be hoped that extensive data along the lines above suggested may be obtained in the near future.

Forest transpiration is of course limited by available water supply derived from precipitation. However, this is automatically taken into account in a large measure, since the type of forest which will grow on a given area and the size attained by the trees is conditioned by rainfall and other environmental factors. While a transpiration loss of 25 inches or more may occur in a full-stocked mature beech forest under favorable conditions, the existence of such a forest stand is proof positive of rainfall sufficiently abundant to support it and to provide the corresponding transpiration and other water losses. In another region with materially lower rainfall an equally dense stand of beech would not be found.

The seasonal transpiration losses can be distributed throughout the different months by taking the transpiration for each month as proportional to the ratio of the evaporative capacity for the given month to the total for the season. The relation between the two as determined by Höhnel's experiments is shown for the growing season, June-September, in Table 18. Separate calcultaions should be made for the growing and dormant seasons because the ratio of transpiration to evaporation rate is higher during the growing than during the dormant forest season. The months of May and October are transition periods for which the ratios of transpiration to evaporation are about midway between their winter and summer values.[6]

[6] Other references on this subject are:
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NOTES ON THE 1922 FREEZE IN SOUTHERN CALIFORNIA.

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It is safe to say that a winter never passes without the occurrence of frost somewhere in the citrus-growing sections of southern California. During many winters, however, the temperature in these districts does not fall low enough to damage citrus fruits. In other winters the damage is slight and is confined to samll areas in the colder localities. In mild winters the light frosts are looked upon by the fruit growers as beneficial, serving to improve the color and flavor of the navel orange.

At intervals of about 10 years, on the average, general heavy freezes have visited the citrus districts, damaging the fruit and trees to the extent of many millions of dollars. These "freezes" partake more of the nature of a cold wave than a frost; in fact, the freeze is a combination of cold wave and frost. A wave of low temperatures advances southward from the Canadian border, on the southern and southwestern borders of a well-developed high-pressure area. A strong, cold northerly wind prevents the normal rise in temperature during the day. When this wind dies out in the evening, the temperature falls with startling rapidity, owning to the low humidity which prevails in southern California under these conditions of pressure distribution.

Strong temperature inversions develop on hillsides and slopes in the citrus districts on calm, frosty nights, but during a freeze differences in temperature between hillside and valley floor are usually slight. The most important factor in limiting or preventing damage during a freeze is the occurrence of a steady wind which continues to blow throughout the night.

Temperatures low enough to damage seriously citrus fruits over a considerable area in southern California occurred in 1913, 1918, and 1922. Freezes occuured in 1913 and 1922, and a serious frost occurred in 1918. In 1913 and 1922 orchards on the higher ground suffered as much damage, in general, as those on the low ground, while in 1918 orchards on the slopes escaped with little or no damage. Some remarkable differences between